ABSORPTION ENHANCEMENT OF PLASMONIC THIN FILM SOLAR CELL COMBINED WITH NANOCAVITY

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ABSTRACT

Plasmonic thin film solar cells have been given a lot of attention from researchers for their absorption capabilities. This study focused on the design of plasmonic thin film solar cell so that the absorption can be optimized. The structures were developed with different materials, geometries and configurations through Finite Element Method via COMSOL Multiphysics software. In order to validate the simulation method, comparison with the results from the previous research has been done first. The proposed design in this study is to build thin film solar cell with the combination of nanoparticle and nanocavity. Positioning gold nanoparticle in plasmonic thin film solar cell was demonstrated in various positions and nanoparticle near the surface has shown to be trapping more light. Semi-ellipse which used as nanocavity shape created an especial surface allowing more of the incident light was absorbed into the solar cell. From these results, the proposed design were structured by using indium tin oxide (ITO), silicon and aluminum as layers in the thin film solar cell with combination of nanoparticle and nanocavity. The result has shown remarkable positive change in absorption rate. The absorption rate for thin film solar cell with only ITO, silicon and aluminum layer has shown lower than thin film solar cell with these layers and the combination of nanocavity and nanoparticle. Detail from the results of this study will support future fabrication on solar cell.

ABSTRAK

Sel solar filem tipis plasmonik telah mendapat banyak perhatian dari para penyelidik untuk keupayaan penyerapannya. Kajian ini memberi tumpuan kepada reka bentuk sel solar filem tipis plasmonik supaya penyerapan dapat dioptimumkan. Strukturnya dibangunkan dengan bahan, geometri dan konfigurasi yang berbeza melalui Kaedah Unsur Terhingga melalui perisian COMSOL Multiphysics. Bagi mengesahkan kaedah simulasi, perbandingan dengan hasil kajian sebelumnya telah dilakukan terlebih dahulu. Reka bentuk yang dicadangkan dalam kajian ini adalah untuk membina sel solar filem nipis dengan gabungan nanopartikel dan rongganano. Menempatkan nanopartikel emas dalam sel solar filem tipis plasmonik ditunjukkan dalam pelbagai posisi dan nanopartikel dekat dengan permukaan telah terbukti menangkap lebih banyak cahaya. Separuh elips yang digunakan sebagai bentuk rongganano mencipta permukaan utama yang memungkinkan lebih banyak cahaya kejadian diserap ke dalam sel suria. Dari hasil ini, reka bentuk yang dicadangkan disusun dengan menggunakan indium timah oksida (ITO), silikon dan aluminium sebagai lapisan dalam sel solar filem nipis dengan kombinasi nanopartikel dan rongganano. Hasilnya menunjukkan perubahan positif dalam kadar penyerapan. Kadar penyerapan sel solar filem nipis dengan hanya menggunakan lapisan ITO, silikon dan aluminium menunjukkan lebih rendah daripada sel solar filem nipis dengan lapisan ini dan gabungan rongganano dan partikel nanopartikel. Perincian dari hasil kajian ini akan menyokong pembuatan fabrikasi sel solar masa depan.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

2D	-	Two dimension
3D	-	Three Dimensions
abs	-	Absolute value
Ag	-	Silver
aSi	-	Amorphous silicon
aSi:H	-	Hydrogenated amorphous silicon
B	-	Magnetic induction
σ	-	Electric conductivity
c	-	Speed of light
C	-	Relative separation of the nanoparticle
d	-	Diameter
D	-	Electric displacement
ε	-	Electric permittivity
ε_r	-	Relative permittivity
E	-	Electric field
E_p	-	Photon energy
E_g	-	Energy bandgap
Ex	-	Electric field at x-axis
Ey	-	Electric field at y-axis
Ez	-	Electric field at z-axis
$F(u)$	-	Arbitrary expression in the dependent variable of u
H	-	Magnetic field
i	-	Complex number
I	-	Intensities of incident light
I_O	-	Transmitted light after passing through the structure
intop_vol	-	Intop volume

intop_surf	-	Intop surface
intWe	-	Integral of electric field
intWm	-	Integral of magnetic field
j	-	Imaginary unit
J	-	Electric current density
k	-	Wave number
K	-	Propagation vector of the incident wave
L	-	Side length
n	-	Normalized normal vector
n	-	Refractive index
na	-	Refractive index, air
nb	-	Refractive index, gold
θ_B	-	Brewster angle
θ_i	-	Angle of incidence
ρ	-	Number of density or concentration
Qabs	-	Efficiency coefficients for absorption
Qext	-	Efficiency coefficients for extinction
Q_i	-	Efficiency coefficient
Qsca	-	Efficiency coefficients for scattering
r	-	Radius
r_p	-	Reflection coefficient, TM
r_s	-	Reflection coefficient, TE
s	-	Second
Si	-	Silicon
Γ	-	Damping rate or collision frequency
t_p	-	Transmission coefficient, TM
t_s	-	Transmission coefficient, TE
μ	-	Magnetic permeability
μ_r	-	Relative permeability
Ω	-	Spatial domain
ω	-	Angular frequency
ω_p	-	Plasma angular frequency of the material

z	-	Unit vector in the z direction
ARC	-	Antireflection coating
BEM	-	Boundary element methods
CdTe	-	Cadmium telluride
CIGS	-	Copper indium gallium diselenide
CPU	-	Central processing unit
DC	-	Direct current
DDA	-	Discrete dipole approximation
Ewfd	-	Electromagnetic wave frequency domain
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
FDTD	-	Finite Different Time Domain
GaAs	-	Gallium arsenide
GHz	-	Gigahertz
IR	-	Infrared
ITO	-	Indium Tin Oxide
LSP	-	Localized surface plasmon
LSPR	-	Localized surface plasmon resonance
LTS	-	Light trapping structures
MHz	-	Megahertz
MIM	-	Metal insulator metal
NP	-	Nanoparticle
PBC	-	Port boundary condition
PDEs	-	Partial differential equation
PEC	-	Perfect electric conductor
PMC	-	Perfect magnetic conductor
PML	-	Perfectly matched layers
PV	-	Photovoltaic
RAM	-	Random access memory
RF	-	Radio frequencies
SBC	-	Scattering boundary condition
SP	-	Surface Plasmon
SPP	-	Surface plasmon polariton

TCO	-	Transparent conductive oxides
TE	-	Transverse electric
THz	-	Terahertz
TM	-	Transverse magnetic
TV	-	Television
UV	-	Ultraviolet

LIST OF PUBLICATIONS

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Sunlight consists of particle or tiny packets of energy which is called as photon. These photons also defined as quantum electromagnetic radiation. It contains various amount of energy that corresponding in solar spectrum into the different wavelength. Solar spectrum is the range in nanometer lies mainly in three regions in the form of visible light, ultraviolet (UV) and infrared (IR). Energy from the sunlight is one of the renewable energy sources which are free, abundant and create clean environment without causing any kind of pollution. Solar cells convert sunlight to electricity through the use of photovoltaic (PV) material. The popular material that has been the chosen for PV cells is silicon which is a semiconductor material. Silicon is non-toxicity, low cost and the most abundant material on earth (Bagher *et al.*, 2015). This material has their characteristics to absorb sunlight. However, photovoltaic cell has been limited due to high amount of material needed for their production and high processing cost (Choudhury & Chowdhury, 2016).

Thin-film is a second-generation of silicon solar cells having the potential to provide viable routes towards minimized the cost problem. Thin film solar cells have several types that are available including copper indium gallium diselenide (CIGS), cadmium telluride (CdTe), and amorphous silicon thin film (Lee, & Abong, 2017). The thickness of thin film mostly in nanometer which more thinner and flexible technology. A thin film solar cell can reduced the production cost by reducing the material used in solar cells but this technique produced a low absorption of photon in the absorbing layers. As a result, thin film solar cell was made up by depositing one or more thin film layer that work to trap the light and as a photon manipulation in thin film solar cell. This solution can minimized the reflection losses in thin absorber layer.

One of the key factors that determine the performance of solar cells is the efficiency of the light absorption process. This is because not all photons hit that the solar cell will be absorbed by semiconductor material. It may reflect off the cell, or transmitted through the cell. However, only photon that can be absorbed into the cell can provide energy to generate electricity. For that reason, many researchers use plasmonic due to their essential role in solar cell application as a way to enhance the absorption of light.

Plasmonic is a phenomena that used light as its main source. Light interacts with metal and goes to moving electron as photon or energy. It makes them oscillate because of the coupling between free electron in metal and electromagnetic field. The electron that oscillates is known as a plasmon. Its oscillation surrounding the atomic lattice sites of a metal as the electron gas (plasma) which defined as fourth matter in the earth besides solid, liquid and gas. Then, when plasmon is coupled with a photon, quasi-particle will present. It is called a polariton or surface plasmon polariton (SPP). The energy is converted into phonons because the polariton propagates along the surface of the metal until it decays by absorption. It happened when plasmon excited at an interface of metal. It also acts as the waves that produce from the interaction between the free electron and electromagnetic wave (Maier, 2007).

Many applications arising in connection with plasmonic is the result of the unique properties of surface plasmon. Plasmonic phenomena have been given a lot of attention from researchers since a few years ago (Ahmed *et al.*, 2007). According to Harry Atwater (2009), “Plasmonics have given photonics the ability to go to the nanoscale.” This means that plasmon can focus light or photon into the smallest places. This can be done in nanoscale level that can produce new developments in nanotechnology. In the meantime, this development has build emerging plasmonics area that offers new paths to enhance the efficiency of thin film solar cells.

Thin film solar cell using plasmonic nanostructures has received attention from researchers with increase understanding about optical properties and development new nanofabrication tools in plasmonic fields. The effective of light affected by plasmonic metallic’s nanostructure have been explored by using amorphous silicon, aSi and gallium arsenide, GaAs in different cell designs (Pala et al., 2009). The entire researchers have focused on enhancing the more absorption and scattering of sunlight (Zia *et al.*, 2006). The basic principal in plasmonic solar cell on their functioning includes absorption and scattering of light was due to the metal nanoparticles deposition. The absorption of light in thin film solar cells are exactly not effectively as well. They need more light to be scattered across the surface to enhance absorption of solar cell for converting light energy to electrical energy (Singh & Verma, 2016). Plasmonic enhanced solar cell will improved the absorption by scattering light using metal nanoparticles that excited at their localized surface plasmon resonance.

Localized surface plasmon resonance (LSPR) is an optical phenomenon when conductive electron that are smaller than the incident wavelength in external electromagnetic field near the metal surface are collectively oscillating and excited at metallic nanoparticles such as gold, silver, copper and aluminum (Catchpole & Polman, 2008). Wavelength for the surface plasmon resonance is dependent on size, material and geometry of metallic nanoparticle (Singh & Verma, 2016).

It is possible to increase the absorption of light or reflection at localize the optical field intensity and selected wavelengths by adjusting the surface plasmon properties, which are controlled by nanostructure of geometric dimensions (Foroutan, Dizaji, & Riahi, 2017). In recent years, many efficient ways in trapping and concentration of light has been studied by exploring the properties of plasmonic using metal film pattern or nanoparticle. Righini *et al.* (2017) make overview about recent results achieved with the same aim which to increasing the energy conversion efficiency, optimize the light trapping and minimize the material usage (Righini *et al.*, 2017). Other than solar cell, many researchers explore the applications of plasmonic nanostructure that can give several potential benefits like biochemical sensing, optical computing and cancer treatments (Heber *et al.*, 2009).

Because of the growing concern of plasmonic systems and subwavelength photonics, the demand for faster and accurate numerical methods becomes very important. This method used to investigate the new science concept and the new design of devices in a variety of applications (Kerrn, 2012).

1.2 Problem statement

Various designs of thin film solar cell have been proposed to enhance the absorption of light. Most of the designs used metal nanoparticle as their method in trapping the light with different material, size, and shape. Some of them used nanocavity as metal film pattern which can boost the amount of light in solar cells and harvest the light. However, most of researchers have focused on nanoparticle or nanocavity only, but there have been little work on the combination of nanoparticle and nanocavity in plasmonic solar cell although both of this structure might solve the problem on reflection loss and enhancing the absorption of light.

The structure which allows nanoscale confinement of the optical field is also a huge disadvantage due to losses incurred. Transmitted or reflected light is considered as a loss in solar cell and therefore optical science is extremely important for minimizing the percentage of reflected light. Light that strikes on the surface of solar cell can be reflected or transmitted the light through the cell. It also can be absorbed or turned the energy into heat or phonon energy. This is natural phenomena that researcher should face to handle the problem in solar cell application.

The absorption of light is very important in generating the high amount of electricity. Light can be determined whether they are absorbed or otherwise by energy of the photon. Therefore, only enough energy photon can make the electron find a state that could be excited to generate electricity. However, generating electricity not only depended on photon energy but also depended on the thickness, structure and type of material. Therefore, structuring solar cell is a challenge to researcher in producing absorption efficiency of solar cell.

Detail information on absorption plasmonic solar cell is not always available in experiment setup for a new advanced material in nanoscale due to high cost, thus providing detail in computational result will support future fabrication on solar cell.

1.3 Significance of study

The efficiency of solar cell depends on how much incoming sunlight energy converted into electricity. This efficiency mostly related with absorption of light that can be captured when incoming photon energy absorbs into solar cell. Therefore, method for light trapping in thin film solar cells is important in order to enhance more absorption of light.

Initially, light trapping techniques was developed for thick active layer of solar cell. However, thin film solar cell have gained attention from researchers as it reduces the material usage and production cost although it is less efficient in absorption of light. So, many methods for light trapping are produced and used in thin film solar cells. Light trapping schemes in thin film solar cell can be modified based on principal of light optical behavior. Modification can be done by adding antireflection coating, controlling geometric parameter, texturing the structure and used plasmonic in solar cell (Tang *et al*., 2014). Light trapping can also be achieved upon novel designs of the device geometry.

Thin film solar cell that used plasmonic reduces more production costs because plasmonic nanostructure has properties that can be controlled by changing their shape and material usage that can be minimized due to their size in nanoscale. Additionally, the reduction in physical thickness of the absorber layers can help reduce the cost of thin film solar cell and produce new development for the design of thin film solar cells.

Plasmonic which is began as an interesting phenomenon by coupling the light trapping electrons near the surface of the metal. Many applications that used plasmonic concept have been proposed. Some of the applications have been commercialized but there are still intense testing and optimization. These development applications can be correlated with the general growth and interest in nanotechnology and nanoscience. This has led to a great variety of both fundamental and practical plasmonic phenomena.

1.4 Objectives

The aim of this project is to analyse the plasmonic thin film solar cell based on nanoparticle and nanocavity design using numerical simulation in 3 dimensions. The specific objectives are:

1. To design and simulate the plasmonic thin film solar cell at different location of nanoparticle and different shapes of nanocavity using Finite Element Method (FEM).

2. To analyse the enhancement absorption of light in plasmonic thin film solar cell combine with nanocavity.

1.5 Scope of study

For this study, plasmonic thin film solar cell combine with nanocavity was analyzed using a numerical simulation to illustrate the structure in three dimensions. The numerical analysis that has been used is Finite Element Method (FEM) using COMSOL Multiphysics software. It focuses on analyzing the enhancement absorption using metal nanoparticle which are gold and silver in sphere shape inside the silicon (Si) layer and semi-ellipse shape as a nanocavity in indium tin oxide (ITO) layer.

1.6 Thesis outline

The rest of the thesis is structured as follows. Second chapter discussed the literature review on the properties of plasmonic, electromagnetic wave, light interaction, etc. The third chapter explained about methodology. In fourth chapter, the analysis of the results was obtained after conducting the methodology. Lastly, the fifth chapter concluded overall studies and some suggestions.

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